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AN APPLICATION OF SYMBOLIC METHODS
TO THE TREATMENT OF MEAN CURVA-
TURES IN HYPERSPACE

A DISSERTATION

SUBMITTED TO THE FACULTY

OF THE

OGDEN GRADUATE SCHOOL OF SCIENCE

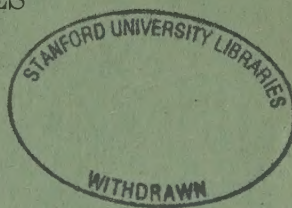
IN CANDIDACY FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

DEPARTMENT OF MATHEMATICS

BY

WILLIAM HUNT BATES



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AN APPLICATION OF SYMBOLIC METHODS TO THE TREATMENT OF MEAN CURVATURES IN HYPERSPACE*

BY

WILLIAM HUNT BATES

This paper is an application of MASCHKE's symbolic method for discussing invariants of quadratic differential forms, as developed in his article, *A Symbolic Treatment of the Theory of Invariants of Quadratic Differential Quantics of n Variables*.† Extensive use is also made of results and methods contained in two later publications, *Differential Parameters of the First Order*,‡ and *The Kronecker-Gaussian Curvature of Hyperspace*.§ Some familiarity with these three articles is implied.

Part I of the present paper is devoted to the study of the curvatures of an n -space R_n in an euclidean $(n+1)$ -space S_{n+1} . In §§ 1–3 the equations and some of the properties of the lines of curvature of R_n in S_{n+1} are developed. In particular, equation (28) gives the n curvatures of the n lines of curvature through a given point of R_n . The coefficients $K_1, \dots, K_n$ of this equation are the so-called curvatures of R_n in S_{n+1} , involving the coefficients a_{ik} and α_{ik} of the two fundamental forms of R_n . With the help of his symbolic method,|| MASCHKE has expressed K_n , when n is even, and K_n^2 , when n is odd, as rational integral functions of the coefficients a_{ik} of the first fundamental form and their derivatives.

In §§ 4–6 similar expressions are derived for all the curvatures $K_{2\nu}$ of even index. It does not seem possible to obtain rational results for the curvatures $K_{2\nu+1}$ of odd index. In § 7, however, it is shown that, with the exception of K_1 , these curvatures are expressible irrationally in terms of the first fundamental quantities and their derivatives.

The symbolic expressions for $K_{2\nu}$ and K_n^2 show at once that they are differential invariants of the first fundamental quadratic form for R_n , and they have meaning as invariants of any quadratic form in n variables. Part II of this paper considers a space R_λ defined in a space R_n ($n > \lambda$), which is not neces-

* Presented to the Society December 31, 1910.

† These Transactions, vol. 4 (1903), pp. 445–469. This paper is referred to hereafter as M. I.

‡ *Ibid.*, vol. 7 (1906), pp. 69–80; referred to as D. P.

§ *Ibid.*, vol. 7 (1906), pp. 81–93; referred to as K.-G. C.

|| In K.-G. C.

where ds_k is the element of the x_k -axis. Represent the direction cosines of the x_k -axis, in the old system, by $\cos(z', x_k), \dots, \cos(z^{n+1}, x_k)$. Then

$$(7) \quad \cos(z^j, x_k) = \frac{dz^j}{ds_k} = \frac{z_k^j dx_k}{\sqrt{a_{kk}} dx_k} = \frac{z_k^j}{\sqrt{a_{kk}}} \quad (j=1, \dots, n+1; k=1, \dots, n).$$

Let ω_{ik} be the angle between the x_i -axis and the x_k -axis. Then

$$(8) \quad \cos \omega_{ik} = \sum_{j=1}^{n+1} \cos(z^j x_i) \cos(z^j x_k) = \sum_{j=1}^{n+1} \frac{z_i^j z_k^j}{\sqrt{a_{ii}} \sqrt{a_{kk}}} = \frac{a_{ik}}{\sqrt{a_{ii}} \sqrt{a_{kk}}} \quad (i, k=1, \dots, n),$$

so that *necessary and sufficient conditions for mutual orthogonality of the axes of the new system are*

$$(9) \quad a_{ik} = 0 \quad (i, k=1, \dots, n; i \neq k).$$

§ 2. General Curves on R_n .

A general curve on R_n may be defined by means of $n-1$ equations,

$$(10) \quad U^2(x_1, \dots, x_n) = \text{const.}, \dots, U^n(x_1, \dots, x_n) = \text{const.}$$

The differential equations of this curve, which we call the U -curve, are

$$(11) \quad \sum_{i=1}^n U_i^2 dx_i = 0, \dots, \sum_{i=1}^n U_i^n dx_i = 0.$$

Its direction is defined by the ratios of $dx_1, \dots, dx_n$ in (11). In order to solve for these differentials, let p be any function of $x_1, \dots, x_n$ which satisfies the condition *

$$D = (p U^2 \dots U^n) = (p U) \neq 0.$$

If A^r denotes the cofactor of p_r in D , equations (11) are identically satisfied by

$$(12) \quad dx_1 = \rho A^1, \dots, dx_n = \rho A^n,$$

where ρ is an arbitrary parameter.

The direction cosines $\xi^j, \dots, \xi^{n+1}$ of the U -curve are found as follows. From (12),

$$(13) \quad \sum_{i=1}^n p_i dx_i = \rho \sum_{i=1}^n p_i A^i = \rho (p U).$$

Then

$$\xi^k = \frac{dz^k}{ds} = \frac{1}{ds} \sum_{i=1}^n z_i^k dx_i = \frac{\rho}{ds} (z^k U),$$

where ds is arc-element of the U -curve. Now

$$\sum_{k=1}^n [\xi^k]^2 = 1 = \sum_{k=1}^{n+1} \left[\frac{\rho}{ds} \right]^2 (z^k U)^2 = \left[\frac{\rho}{ds} \right]^2 (f U)^2.$$

* See M. I., § 2, for an explanation of this invariantive notation.

Hence

$$\frac{\rho}{ds} = \frac{1}{\sqrt{(fU)^2}}.$$

Then the direction cosines of the U -curve on R_n , referred to the original system of axes, are

$$(14) \quad \xi' = \frac{(z' U)}{\sqrt{(fU)^2}}, \dots, \xi^{n+1} = \frac{(z^{n+1} U)}{\sqrt{(fU)^2}}.$$

If there is given also a V -curve on R_n by equations similar to (10), its direction cosines may be written

$$(15) \quad \eta' = \frac{(z' V)}{\sqrt{(fV)^2}}, \dots, \eta^{n+1} = \frac{(z^{n+1} V)}{\sqrt{(fV)^2}}.$$

If ω is the angle between the two curves, we have from (14) and (15)

$$(16) \quad \cos \omega = \sum_{i=1}^{n+1} \xi^i \eta^i = \sum_{i=1}^{n+1} \frac{(z^i U)(z^i V)}{\sqrt{(fU)^2} \sqrt{(fV)^2}} = \frac{(fU)(fV)}{\sqrt{(fU)^2} \sqrt{(fV)^2}}.$$

Thus a necessary and sufficient condition for orthogonality of the two curves is

$$(17) \quad (fU)(fV) = 0.$$

Equation (17) also defines the orthogonal trajectories of a system of U -curves on R_n . An illustration is found in the case of curves on an ordinary surface.

§ 3. Lines of Curvature on R .

A line L drawn on R_n such that the normals to R_n along L (with respect to the enclosing space S_{n+1}) generate a developable surface is called* a line of curvature of R_n in S_{n+1} .

At a point P of R_n there is a unique normal to R_n in S_{n+1} . Let the direction cosines of this normal be $\zeta', \dots, \zeta^{n+1}$. Choose P as origin of the system of x -axes on R_n . Then, since the normal to R_n at P is orthogonal to every direction on R_n at P , we have from (7)

$$(18) \quad \sum_{i=1}^{n+1} \zeta^i z_k^i = 0 \quad (k=1, \dots, n).$$

The coefficients α_{ik} of the first fundamental form of R_n , given in (3) are the first fundamental quantities. The second fundamental quantities are defined by the equations

$$\alpha_{ik} = \sum_{j=1}^{n+1} \zeta^j z_{ik}^j \quad (i, k=1, \dots, n).$$

* Cf. BIANCHI, *Lezioni di Geometria Differenziale*, vol. I, p. 125.

By differentiating (18), one obtains

$$(19) \quad \alpha_{ik} = \sum_{j=1}^{n+1} \zeta^j z_{ik}^j = - \sum_{j=1}^{n+1} \zeta_i^j z_k^j \quad (i, k=1, \dots, n).$$

The letters g and γ are to be used in this paper as symbols of the second fundamental quantities

$$(20) \quad \alpha_{ik} = g_i g_k = \gamma_i \gamma_k = \alpha_{ki}.$$

Let C be the curve of S_{n+1} which is the envelope of the normals along L . Let $M(z', \dots, z^{n+1})$ be any point of L , and $\bar{M}(\bar{z}', \dots, \bar{z}^{n+1})$ be the point where the normal at M meets C . Denote by r the distance $M\bar{M}$, which is positive or negative according to the direction of $\bar{M}$ from M . Then

$$(21) \quad \bar{z}' = z' - r\zeta', \dots, \bar{z}^{n+1} = z^{n+1} - r\zeta^{n+1}.$$

Take derivatives of equations (21) with respect to the arc s of L . Then, since C is envelope of the normals along L ,

$$(22) \quad \begin{aligned} \frac{d\bar{z}'}{ds} &= \frac{dz'}{ds} - r \frac{d\zeta'}{ds} - \zeta' \frac{dr}{ds} = q\zeta', \\ &\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\ \frac{d\bar{z}^{n+1}}{ds} &= \frac{dz^{n+1}}{ds} - r \frac{d\zeta^{n+1}}{ds} - \zeta^{n+1} \frac{dr}{ds} = q\zeta^{n+1}, \end{aligned}$$

where q is a factor of proportionality to be determined. Multiply equations (22) by $\zeta', \dots, \zeta^{n+1}$ in order and add. We get

$$(23) \quad q \sum_{i=1}^{n+1} [\zeta^i]^2 = \sum_{i=1}^{n+1} \zeta^i \frac{dz^i}{ds} - r \sum_{i=1}^{n+1} \zeta^i \frac{d\zeta^i}{ds} - \frac{dr}{ds} \sum_{i=1}^{n+1} [\zeta^i]^2.$$

Now

$$\sum_{i=1}^{n+1} [\zeta^i]^2 = 1, \quad \sum_{i=1}^{n+1} \zeta^i \frac{d\zeta^i}{ds} = 0, \quad \sum_{i=1}^{n+1} \zeta^i \frac{dz^i}{ds} = 0,$$

since $\zeta', \dots, \zeta^{n+1}$ are direction cosines of the normal and $dz'/ds, \dots, dz^{n+1}/ds$ are direction cosines of L . Substituting these results in (23), one obtains

$$q = - \frac{dr}{ds}.$$

Then equations (22) give

$$(24) \quad \frac{dz'}{ds} = r \frac{d\zeta'}{ds}, \dots, \frac{dz^{n+1}}{ds} = r \frac{d\zeta^{n+1}}{ds},$$

or

$$(25) \quad \frac{dz'}{d\zeta'} = \frac{dz^2}{d\zeta^2} = \dots = \frac{dz^{n+1}}{d\zeta^{n+1}} = r.$$

This result is expressed in curvilinear coördinates as follows:

$$\begin{aligned} z'_1 dx_1 + \cdots + z'_n dx_n &= r(\xi'_1 dx_1 + \cdots + \xi'_n dx_n), \\ z_1^{n+1} dx_1 + \cdots + z_n^{n+1} dx_n &= r(\xi_1^{n+1} dx_1 + \cdots + \xi_n^{n+1} dx_n). \end{aligned}$$

Multiply these equations in order by $z'_k, \dots, z_k^{n+1}$ and add. We find

$$\sum_{i=1}^{n+1} z_k^i z_1^i dx_1 + \cdots + \sum_{i=1}^{n+1} z_k^i z_n^i dx_n = r \left[\sum_{i=1}^{n+1} z_k^i \xi_1^i dx_1 + \cdots + \sum_{i=1}^{n+1} z_k^i \xi_n^i dx_n \right].$$

Then, by (4) and (19),

$$(26) \quad a_{k1} dx_1 + \cdots + a_{kn} dx_n = -r [\alpha_{k1} dx_1 + \cdots + \alpha_{kn} dx_n] \quad (k=1, \dots, n).$$

Equations (26) hold for every line of curvature on R_n . Conversely, if equations (26) be true for any curve L on R_n , then there exists a curve C in S_{n+1} whose tangents are normal to R_n along L , so that L is a line of curvature on R_n by definition.

When equations (26) are written in the form

$$(27) \quad \begin{aligned} (a_{11} + \alpha_{11}r) dx_1 + \cdots + (a_{1n} + \alpha_{1n}r) dx_n &= 0, \\ (a_{n1} + \alpha_{n1}r) dx_1 + \cdots + (a_{nn} + \alpha_{nn}r) dx_n &= 0, \end{aligned}$$

it is evident that the curvature $(1/r)$ of each line of curvature through a point P on R_n must satisfy the condition

$$(28) \quad \begin{vmatrix} a_{11} + \alpha_{11}r & a_{12} + \alpha_{12}r & \cdots & a_{1n} + \alpha_{1n}r \\ a_{21} + \alpha_{21}r & a_{22} + \alpha_{22}r & \cdots & a_{2n} + \alpha_{2n}r \\ \cdot & \cdot & \cdot & \cdot \\ a_{n1} + \alpha_{n1}r & a_{n2} + \alpha_{n2}r & \cdots & a_{nn} + \alpha_{nn}r \end{vmatrix} = 0,$$

since otherwise equations (27) would have no solution except

$$dx_1 = dx_2 = \cdots = dx_n = 0.$$

Hence the reciprocals of the roots of (28) are exactly the curvatures of the n lines of curvature through a point P on R_n .

The coefficients of r in (28) are called the curvatures of R_n in S_{n+1} and are discussed in §§ 4-7. Before proceeding to that discussion, we derive an important property of lines of curvature.

Expressing (26) in symbolic notation, one finds

$$(29) \quad f_k \sum_{i=1}^n f_i dx_i = -rg_k \sum_{i=1}^n g_i dx_i \quad (k=1, \dots, n)$$

If now a line of curvature be represented as a U -curve (10), one gets from (13) and (29)

$$(30) \quad f_k(fU) = -rg_k(gU) \quad (k=1, \dots, n).$$

A symmetrical expression for r is obtained by multiplying equations (30) in order by the cofactors of $f_1, \dots, f_n$ in (fU) and adding:

$$(31) \quad r = -\frac{(fU)^2}{(gU)^2}.$$

If any two lines of curvature through P be given as U and V -curves, and their respective curvatures be denoted by $1/r'$ and $1/r''$, one gets from (30)

$$g_1(gU) = -\frac{1}{r'}f_1(fU), \dots, g_n(gU) = -\frac{1}{r'}f_n(fU),$$

$$g_1(gV) = -\frac{1}{r''}f_1(fV), \dots, g_n(gV) = -\frac{1}{r''}f_n(fV).$$

Multiply the equations of the first line in order by the cofactors of $f_1, \dots, f_n$ in (fV) and add. Also multiply the equations of the second line in order by the cofactors of $f_1, \dots, f_n$ in (fU) and add. Then

$$(gU)(gV) = -\frac{1}{r'}(fU)(fV) = -\frac{1}{r''}(fU)(fV),$$

so that either $r' = r''$ or $(fU)(fV) = 0$. Hence by (17) we have

Theorem I. *Any two distinct lines of curvature through an ordinary point P of R_n are orthogonal to each other.*

If the lines of curvature through P be taken as parameter lines, then, by (9),

$$\alpha_{ik} = 0 \quad (i \neq k)$$

It follows at once from (26) that also

$$\alpha_{ik} = 0 \quad (i, k=1, \dots, n; i \neq k).$$

Theorem II. *If the lines of curvature at an ordinary (not umbilic) point of R_n be taken as parameter lines, then*

$$\alpha_{ik} = 0, \quad \alpha_{ik} = 0 \quad (i, k=1, \dots, n; i \neq k).$$

§ 4. Definition of the Curvatures of R_n in S_{n+1} .

Equation (28) may be written in the form

$$(32) \quad H_0 + H_1r + \dots + H_{n-1}r^{n-1} + H_nr^n = 0,$$

where*

$$H_0 = |\alpha_{ik}| = 1/\beta^2, \quad H_n = |\alpha_{ik}|,$$

* M. I., (9).

while for $j = 1, \dots, n$, H_j is the sum of all the determinants obtained from $|a_{ik}|$ by replacing in all possible ways j columns of $|a_{ik}|$ by the corresponding columns of $|\alpha_{ik}|$. Dividing (32) by H_0 one obtains

$$(33) \quad 1 + K_1 r + \dots + K_{n-1} r^{n-1} + K_n r^n = 0.$$

The coefficient K_n (the product of all the curvatures) is the Kronecker-Gaussian curvature of hyperspace. It has been shown to be expressible in terms of the first fundamental quantities and their derivatives (cf. K-G. C.). In this paper the coefficients of (33) are called the n curvatures of R_n in S_{n+1} . By definition

$$(34) \quad K_1 = \beta^2 \sum_{i, k}^{1, \dots, n} \alpha_{ik} A_k^i, \quad K_2 = \beta^2 \sum_{i_1 i_2, k_1 k_2}^{1, \dots, n} \begin{vmatrix} \alpha_{i_1 k_1} & \alpha_{i_1 k_2} \\ \alpha_{i_2 k_1} & \alpha_{i_2 k_2} \end{vmatrix} \cdot A_{k_1 k_2}^{i_1 i_2} = \sum_{i_1 i_2, k_1 k_2}^{1, \dots, n} \Delta_{k_2 k_2}^{i_1 i_2} A_{k_1 k_2}^{i_1 i_2}, \dots,$$

$$K_m = \beta^2 \sum_{i_1 \dots i_m, k_1 \dots k_m}^{1, \dots, n} \Delta_{k_1 \dots k_m}^{i_1 \dots i_m} \cdot A_{k_1 \dots k_m}^{i_1 \dots i_m} \quad (m = 1, \dots, n),$$

where A_k^i is the cofactor of a_{ik} in $|a_{ik}|$, $A_{k_1 k_2}^{i_1 i_2}$ is the algebraic complement of

$$\begin{vmatrix} a_{i_1 k_1} & a_{i_1 k_2} \\ a_{i_2 k_1} & a_{i_2 k_2} \end{vmatrix}$$

in $|a_{ik}|$, while $\Delta_{k_1 k_2}^{i_1 i_2}$ is the second minor of $|\alpha_{ik}|$ indicated for K_2 above; and similarly for the A 's and Δ 's in K_m . Both sets $i_1, \dots, i_m$ and $k_1, \dots, k_m$ are considered as being in ascending numerical order.

§ 5. Invariant Symbolic Forms of $K_1, \dots, K_n$.

If F_k^i be the cofactor of f_k^i in the functional determinant $\{f', \dots, f^n\}$, Maschke* has shown that

$$A_k^i = \frac{1}{(n-1)!} F_i' F_k'.$$

Thus

$$K_1 = \beta^2 \sum_{i, k}^{1, \dots, n} \alpha_{ik} A_k^i = \frac{\beta^2}{(n-1)!} \sum_{i, k}^{1, \dots, n} g_i g_k F_i' F_k'.$$

$$= \frac{\beta^2}{(n-1)!} \{gf^2 \dots f^n\}^2 = \frac{1}{(n-1)!} (gf)^2.$$

This suggests a method for reducing all the curvatures to convenient invariant forms. Let $F_{i_1 \dots i_m}^{1 \dots m}$ be the algebraic complement of

$$\begin{vmatrix} f_{i_1}' & \dots & f_{i_m}' \\ \dots & \dots & \dots \\ f_{i_1}^m & \dots & f_{i_m}^m \end{vmatrix}$$

* M. I., p. 450.

in $\{f' \dots f^n\}$. Then the product $F_{i_1 \dots i_m}^{1 \dots m} \cdot F_{k_1 \dots k_m}^{1 \dots m}$ may be written

$$\begin{vmatrix} f_1^{m+1} \dots f_{i_1-1}^{m+1} f_{i_1+1}^{m+1} \dots f_{i_m-1}^{m+1} f_{i_m+1}^{m+1} \dots f_{i_n}^{m+1} \\ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\ f_1^n \dots f_{i_1-1}^n f_{i_1+1}^n \dots f_{i_m-1}^n f_{i_m+1}^n \dots f_{i_n}^n \end{vmatrix} F_{k_1 \dots k_m}^{1 \dots m}.$$

If the first determinant of this product be expanded, one finds $(n-m)!$ terms of the form

$$(-1)^\mu f_1 \dots f_{i_1-1} f_{i_1+1} \dots f_{i_m-1} f_{i_m+1} \dots f_n \cdot F_{k_1 \dots k_m}^{1 \dots m},$$

where the suppressed upper indices of the first factor are understood to be any permutation of the numbers $m+1, \dots, n$, while μ represents the number of inversions in the permutation. Since the equivalent symbols $f^{m+1}, \dots, f^n$ may be interchanged in all possible ways without altering the value of the term, let them be so interchanged for each term as to reduce the first factor to $(-1)^\mu$ times the principal diagonal term of $F_{i_1 \dots i_m}^{1 \dots m}$. This causes an interchange of rows in the second (determinant) factor $F_{k_1 \dots k_m}^{1 \dots m}$ so that it becomes in each case $(-1)^\mu$ times its original form. Hence the above product becomes

$$(n-m)! f_1^{m+1} \dots f_{i_1-1}^{i_1+m-1} f_{i_1+1}^{i_1+m} \dots f_{i_m-1}^{i_m} f_{i_m+1}^{i_m+1} \dots f_n^n \cdot F_{k_1 \dots k_m}^{1 \dots m}.$$

Multiplying each f into the corresponding row of the determinant $F_{k_1 \dots k_m}^{1 \dots m}$ (which has a form similar to that given above for $F_{i_1 \dots i_m}^{1 \dots m}$), we have

$$F_{i_1 \dots i_m}^{1 \dots m} \cdot F_{k_1 \dots k_m}^{1 \dots m} = (n-m)! A_{k_1 \dots k_m}^{i_1 \dots i_m},$$

or

$$(35) \quad A_{k_1 \dots k_m}^{i_1 \dots i_m} = \frac{1}{(n-m)!} F_{i_1 \dots i_m}^{1 \dots m} \cdot F_{k_1 \dots k_m}^{1 \dots m}.$$

Also

$$\Delta_{\substack{i_1 \dots i_m \\ k_1 \dots k_m}} = \frac{\begin{vmatrix} \alpha_{i_1 k_1} \dots \alpha_{i_m k_m} \\ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\ \alpha_{i_m k_1} \dots \alpha_{i_m k_m} \end{vmatrix}}{\begin{vmatrix} g'_{i_1} g'_{k_1} \dots g'_{i_1} g'_{k_m} \\ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\ g_{i_m}^m g_{k_1}^m \dots g_{i_m}^m g_{k_m}^m \end{vmatrix}} = \frac{\begin{vmatrix} g'_{i_1} g'_{k_1} \dots g'_{i_1} g'_{k_m} \\ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\ g_{i_m}^m g_{k_1}^m \dots g_{i_m}^m g_{k_m}^m \end{vmatrix}}{\begin{vmatrix} g'_{i_1} \dots g'_{i_m} \\ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\ g_{i_1}^m \dots g_{i_m}^m \end{vmatrix}} \cdot \frac{\begin{vmatrix} g'_{k_1} \dots g'_{k_m} \\ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\ g_{k_1}^m \dots g_{k_m}^m \end{vmatrix}}{\begin{vmatrix} g_{k_1}^m \dots g_{k_m}^m \end{vmatrix}},$$

$$(36) \quad \Delta_{\substack{i_1 \dots i_m \\ k_1 \dots k_m}} = \frac{1}{m!} \frac{\begin{vmatrix} g'_{i_1} \dots g'_{i_m} \\ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\ g_{i_1}^m \dots g_{i_m}^m \end{vmatrix}}{\begin{vmatrix} g_{i_1}^m \dots g_{i_m}^m \end{vmatrix}} \cdot \frac{\begin{vmatrix} g'_{k_1} \dots g'_{k_m} \\ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\ g_{k_1}^m \dots g_{k_m}^m \end{vmatrix}}{\begin{vmatrix} g_{k_1}^m \dots g_{k_m}^m \end{vmatrix}}.$$

Substituting (35) and (36) in (34), one finds, by a well-known theorem of determinants,

$$(37) \quad K_m = \frac{1}{m!(n-m)!} (g' \dots g^m f^{m+1} \dots f^n)^2 = \frac{1}{m!(n-m)!} (g' \dots g^m f)^2.$$

In particular,

$$K_1 = \frac{1}{(n-1)!} (g^f)^2 = \Delta_1 g,$$

where, by M. 1. (22), $\Delta_1 g$ is the first differential parameter of the first quadratic form ().

This gives Maschke's expression * for K_n when n is even :

$$K_n = \frac{1}{n![(n-1)!]^{n/2}} ((fa)' \cdots (fa)^n)(f) \quad (n \text{ even}).$$

Theorem. *The mean curvatures $K_{2\nu}$, with even subscript, are represented in (40) as rational integral functions of the coefficients of the first fundamental form and their derivatives.*

§ 7. *Expression of $K_{2\nu+1}$ in terms of the first Fundamental Quantities and Derivatives, when ν is greater than zero.*

Use is made of the determinant theorem

$$(41) \quad \Delta_{\substack{i_1 \dots i_{2\nu+1} \\ k_1 \dots k_{2\nu+1}}}^2 = \frac{1}{2} \sum_{j,r}^{1, \dots, n} \begin{vmatrix} \alpha_{ij k_s} & \alpha_{ij k_t} \\ \alpha_{i_r k_s} & \alpha_{i_r k_t} \end{vmatrix} \begin{vmatrix} D_{ij k_s} & D_{ij k_t} \\ D_{i_r k_s} & D_{i_r k_t} \end{vmatrix} \quad (s, t = 1, \dots, 2\nu+1; s \neq t),$$

where $\nu \neq 0$ and the D 's are cofactors of the corresponding α 's in $\Delta_{\substack{i_1 \dots i_{2\nu+1} \\ k_1 \dots k_{2\nu+1}}}^2$ and are therefore all of even order and expressible by (39). The results are

$$\begin{aligned} D_{ij k_s} &= \frac{\epsilon^\nu}{(2\nu)!} F'_{ij} (FA)'_{k_s}, & D_{ij k_t} &= \frac{\epsilon^\nu}{(2\nu)!} \Phi'_{ij} (\Phi B)'_{k_t}, \\ D_{i_r k_s} &= \frac{\epsilon^\nu}{(2\nu)!} F'_{i_r} (FA)'_{k_s}, & D_{i_r k_t} &= \frac{\epsilon^\nu}{(2\nu)!} \Phi'_{i_r} (\Phi B)'_{k_t}, \end{aligned}$$

where F'_{ij} is the cofactor of f'_{ij} in $\{f'_{i_1} \cdots f'_{i_{2\nu+1}}\}$, $\dots$, $(\Phi B)'_{k_t}$ is the cofactor of $(\phi b)'_{k_t}$ in $\{(\phi b)'_{k_1} \cdots (\phi b)'_{k_{2\nu+1}}\}$. Also, by M. I. (120),

$$\begin{vmatrix} \alpha_{ij k_s} & \alpha_{ij k_t} \\ \alpha_{i_r k_s} & \alpha_{i_r k_t} \end{vmatrix} = \epsilon (fc)'_{k_s} (\phi c)'_{k_t} \begin{vmatrix} f'_{ij} & \phi'_{ij} \\ f'_{i_r} & \phi'_{i_r} \end{vmatrix},$$

Substituting in (41), we find

$$\begin{aligned} \Delta_{\substack{i_1 \dots i_{2\nu+1} \\ k_1 \dots k_{2\nu+1}}}^2 &= \frac{\epsilon^{2\nu+1}}{[(2\nu)!]^2} (fc)'_{k_s} (FA)'_{k_s} (\phi c)'_{k_t} (\Phi B)'_{k_t} \\ &\quad \times \frac{1}{2} \sum_{j,r}^{1, \dots, 2\nu+1} \begin{vmatrix} f'_{ij} & \phi'_{ij} \\ f'_{i_r} & \phi'_{i_r} \end{vmatrix} \begin{vmatrix} F'_{ij} & \Phi'_{ij} \\ F'_{i_r} & \Phi'_{i_r} \end{vmatrix}. \end{aligned}$$

This last sum expands into

$$\begin{aligned} \frac{1}{2} \sum_{j,r}^{1, \dots, 2\nu+1} &[f'_{ij} F'_{ij} \phi'_{i_r} \Phi'_{i_r} - f'_{ij} \Phi'_{ij} \phi'_{i_r} F'_{i_r} - f'_{i_r} \Phi'_{i_r} \phi'_{ij} F'_{ij} + f'_{i_r} F'_{i_r} \phi'_{ij} \Phi'_{ij}] \\ &= \begin{vmatrix} \{f'_{i_1} \cdots f'_{i_{2\nu+1}}\} & \{f'_{i_1} \phi_{i_2}^2 \cdots \phi_{i_{2\nu+1}}^{2\nu+1}\} \\ \{\phi'_{i_1} f_{i_2}^2 \cdots f_{i_{2\nu+1}}^{2\nu+1}\} & \{\phi'_{i_1} \cdots \phi_{i_{2\nu+1}}^{2\nu+1}\} \end{vmatrix}, \end{aligned}$$

so that

$$\begin{aligned} \Delta_{\substack{i_1 \dots i_{2\nu+1} \\ k_1 \dots k_{2\nu+1}}}^2 &= \frac{\epsilon^{2\nu+1}}{[(2\nu)!]^2} (fc)'_{k_s} (FA)'_{k_s} (\phi c)'_{k_t} (\Phi B)'_{k_t} \\ &\quad \times \begin{vmatrix} \{f'_{i_1} \cdots f'_{i_{2\nu+1}}\} & \{f'_{i_1} \phi_{i_2}^2 \cdots \phi_{i_{2\nu+1}}^{2\nu+1}\} \\ \{\phi'_{i_1} f_{i_2}^2 \cdots f_{i_{2\nu+1}}^{2\nu+1}\} & \{\phi'_{i_1} \cdots \phi_{i_{2\nu+1}}^{2\nu+1}\} \end{vmatrix}. \end{aligned}$$

* K.-G. C., (29).

By (41) this equation holds for all values of s and t from 1 to $2\nu + 1$ except $s = t$. When $s = t$, the second member vanishes. Sum the equations given by using all values of s and t from 1 to $2\nu + 1$ and divide by $(2\nu + 1)2\nu$; also multiply by β^4 . Then

$$(42) \quad \beta^4 \Delta_{i_1 \dots i_{2\nu+1}}^2 = \frac{\varepsilon^{2\nu+1}}{(2\nu + 1)(2\nu)[(2\nu)!]^2} ((fc)'_{k_1}(fa)_{k_2}^2 \dots (fa)_{k_{2\nu+1}}^{2\nu+1}) \\ \times ((\phi c)'_{k_1}(\phi b)_{k_2}^2 \dots (\phi b)_{k_{2\nu+1}}^{2\nu+1}) \left| \begin{array}{cc} \{f'_{i_1} \dots f_{i_{2\nu+1}}^{2\nu+1}\} & \{f'_{i_1} \phi_{i_2}^2 \dots \phi_{i_{2\nu+1}}^{2\nu+1}\} \\ \{\phi'_{i_1} f_{i_2}^2 \dots f_{i_{2\nu+1}}^{2\nu+1}\} & \{\phi'_{i_1} \dots \phi_{i_{2\nu+1}}^{2\nu+1}\} \end{array} \right|.$$

And by (34)

$$K_{2\nu+1} = \sum_{i_1 \dots i_{2\nu+1} k_1 \dots k_{2\nu+1}}^{1, \dots, n} [\beta^4 \Delta_{i_1 \dots i_{2\nu+1}}^2]_{k_1 \dots k_{2\nu+1}}^{\frac{1}{2}} A_{i_1 \dots i_{2\nu+1}} \quad (\nu > 0).$$

Thus by (34) and (42) we have $K_{2\nu+1} (\nu > 0)$ expressed in terms of the first fundamental quantities and derivatives (but only in the irrational form of a sum of square roots).

The case of K_1 presents special difficulty:

$$K_1 = \beta^2 \sum_{ik}^{1, \dots, n} \alpha_{ik} A_k^i.$$

In K.-G. C. (p. 24), Maschke suggests a method for expressing the α 's in terms of the a 's when n is odd. His formula (24) should, however, be written,

$$(43) \quad \alpha_{11} \Delta^{n-2} = \begin{vmatrix} A_{22} & \dots & A_{2n} \\ A_{n2} & \dots & A_{nn} \end{vmatrix}.$$

If n is odd, the elements of the second member of (43) are of even order, and therefore expressible by (39), and similarly for every α . But Δ itself is of odd order, and is raised to an odd power ($n - 2$ instead of $n - 1$).^{*} Equation (43) is true also for even values of n , so that the α 's are always expressible by (43) in terms of the first fundamental quantities and derivatives (if $n > 2$), but in all cases irrationally.

Using (43), the author has calculated irrational values of K_1 when n is greater than two; but the notation is so complicated that the presentation of the results seems impracticable, if not also useless.[†]

If $2\nu + 1 = n$, the sum reduces to a single term and formulas (34) and (42)

^{*} Cf. BÔCHER, *Introduction to Higher Algebra*, § 11.

[†] In a recent paper the author has calculated the value of K_1 as well as of the other curvatures of odd subscript, for a space of $n - 1$ dimensions defined in R_n by the equation $U(x_1 \dots x_n) = 0$. These values involve only the coefficients of the first fundamental form of R_n and their derivatives, together with the function U .

give a rational value for K_n^2 ,

$$(44) \quad K_n^2 = \beta^4 \Delta^2 = \frac{\epsilon^{n+2}}{n(n-1)} \left((fc)'(fa)^2 \dots (fa)^n \right) \left((\phi c)'(\phi b)^2 \dots (\phi b)^n \right) \begin{vmatrix} (f) & (f'\phi) \\ (\phi'f) & (\phi) \end{vmatrix}.$$

By the method used in K.-G. C. (p. 86), this may be reduced to Maschke's form (31):*

$$(45) \quad K_n^2 = \frac{1}{n[(n-1)!]^{n+2}} \left((fc)'(fa)^2 \dots (fa)^n \right) \left((\phi c)'(\phi b)^2 \dots (\phi b)^n \right) (f'\phi'f)(f^2\phi^2\phi).$$

The rather unsatisfactory results of this section are then as follows:

If n is odd, K_n^2 is expressed by (45) as a rational function of the first fundamental quantities and their derivatives. Equations (34) and (42) give irrational expressions for the curvatures of odd index except K_1 , for which no expression is here given.

PART II.

INVARIANTS OF R_λ IN R_n .

The quantities $K_{2\nu}$ and K_n^2 , for n odd, are by their forms (40) and (45) differential invariants of the first fundamental quadratic form (3). When (3) defines the arc-element of a space R_n of n dimensions contained in an euclidean space S_{n+1} of $n+1$ dimensions, these K 's have the geometric meaning already assigned to them. It is our object † to find corresponding invariants of a space R_λ of λ dimensions, represented as differential parameters of a general space R_n of higher dimensions containing R_λ .

§ 1. Definitions and Preliminary Formulas.

In the general space R_n , of n dimensions, whose coördinates are $x_1, \dots, x_n$ and whose arc-element is defined by equation (3), let the space R_λ of λ dimensions ($\lambda < n$) be defined by the $n - \lambda$ equations

$$(46) \quad U^{\lambda+1}(x_1, \dots, x_n) = \text{const.}, \dots, U^n(x_1, \dots, x_n) = \text{const.}$$

If λ other arbitrarily chosen functions of $x_1, \dots, x_n$, say $u', \dots, u^\lambda$, such that

$$\Delta = (u' \dots u^\lambda U^{\lambda+1} \dots U^n) \neq 0,$$

are adjoined to these, the space R_λ may also be represented in parametric form

$$(47) \quad x_1 = x_1(u', \dots, u^\lambda), \dots, x_n = x_n(u', \dots, u^\lambda),$$

* In MASCHKE's reduction there are two slight numerical errors which balance each other. His equation (30) differs from (44) above in that he has divided by n^2 instead of by $n(n-1)$; while in his reduction of (30) there are $n-1$ of the terms which become equal, instead of n .

† Cf. K.-G. C., § 5.

If we use the symbols of form (51), the invariants $K_{2\nu}$ and K_λ^2 (λ odd) of R_λ may be written, by (40) and (45),

$$(53) \quad (2\nu)!(\lambda - 2\nu)![(\lambda - 1)!]^\nu K_{2\nu} = G_{2\nu} = (\bar{f}a)' \dots (\bar{f}a)^{2\nu} \bar{f}^{2\nu+1} \dots \bar{f}^\lambda (\bar{f}' \dots \bar{f}^\lambda),$$

$$(54) \quad \lambda [(\lambda - 1)!]^{\lambda+2} K_\lambda^2 = G_\lambda^2 = ((\bar{f}c)'(\bar{f}a)^2 \dots (\bar{f}a)^\lambda) \\ \times ((gc)'(gb)^2 \dots (gb)^\lambda) (\bar{f}'g'\bar{f}^3 \dots \bar{f}^\lambda) (\bar{f}^2g^2 \dots g^\lambda),$$

where $G_{2\nu}$ and G_λ^2 are introduced merely for convenience. In all invariantive brackets containing the new symbols, of the quadratic form (51), the differentiation is with respect to the λ variables $u', \dots, u^\lambda$. This is indicated sufficiently by the German type and the number of symbols inside the brackets. β_u is defined by the equation

$$(\bar{f}' \dots \bar{f}^\lambda) = \beta_u \{ \bar{f}' \dots \bar{f}^\lambda \}.$$

We now proceed to compute the values of the invariantive expressions used in (53) and (54) in terms of the symbols of the first fundamental form (3), of R_n and the functions $U^{\lambda+1}, \dots, U^n$ which define R_λ in R_n .

By means of (52) and D. P. (3), we obtain

$$\{ \bar{f}' \dots \bar{f}^\lambda \} = \frac{1}{\Delta^\lambda} \{ f' \dots f^\lambda U \} \{ u' \dots u^\lambda U \}^{\lambda-1} = \frac{1}{\Delta} \{ f' \dots f^\lambda U \},$$

so that

$$(55) \quad \frac{1}{\beta_u} (\bar{f}' \dots \bar{f}^\lambda) = \frac{1}{\beta_\Delta} (f' \dots f^\lambda U).$$

To calculate the value of β_u , square (55) and simplify the result by placing $(\bar{f}' \dots \bar{f}^\lambda)^2 = \lambda!$, according to M. I. (17), and $(f' \dots f^\lambda U)^2 = \lambda!(n - \lambda)!\Delta^{n-\lambda}U$ by (38). This gives

$$(56) \quad \beta_u = \omega\beta\Delta, \quad \omega = \sqrt{\frac{1}{(n - \lambda)!\Delta^{n-\lambda}U}}.$$

Then

$$(\bar{f}' \dots \bar{f}^\lambda) = \omega(f' \dots f^\lambda U).$$

The other invariantive forms in (53) and (54) are reduced by the same method, and by interchanging equivalent symbols, giving*

$$(57) \quad (\bar{f}'g'\bar{f}^3 \dots \bar{f}^\lambda) = \omega(f'g'f^3 \dots f^\lambda U), \quad (\bar{f}^2g^2 \dots g^\lambda) = \omega(f^2g^2 \dots \phi^\lambda U), \\ ((\bar{f}a)' \dots (\bar{f}a)^{2\nu} \bar{f}^{2\nu+1} \dots \bar{f}^\lambda) \\ = \omega(\omega(faU)', \omega(faU)^2, \dots, \omega(faU)^{2\nu}, f^{2\nu+1} \dots f^\lambda U),$$

* Inside the invariantive brackets, we have followed MASCHKE's custom of omitting commas between symbols, except where ambiguity might occur. Cf. M. I., p. 448.

By applying D. P. (1) to the first two brackets, and proceeding as above, one finds $T=0$ also for even values of k .

With the help of these results (58) becomes

$$G_{2\nu} = \omega^{2\nu+2} ((faU)' \dots (faU)^{2\nu} f^{2\nu+1} \dots f^\lambda U) (f' \dots f^\lambda U).$$

Then, by (53) and (56),

$$(59) \quad K_{2\nu} = \frac{(\lambda-1)! ((faU)' \dots (faU)^{2\nu} f^{2\nu+1} \dots f^\lambda U) (f' \dots f^\lambda U)}{(2\nu)! (\lambda-2\nu)! [(\lambda-1)! (n-\lambda)! \Delta^{n-\lambda} U]^{\nu+1}}.$$

If $2\nu = \lambda$, (59) becomes

$$(60) \quad K_\lambda = \frac{((faU)' \dots (faU)^\lambda U) (f' \dots f^\lambda U)}{\lambda! [(\lambda-1)! (n-\lambda)! \Delta^{n-\lambda} U]^{(\lambda+2)/2}},$$

which agrees with Maschke's form, K.-G. C. (60). The symbols f and a belong to the quadratic form (3), expressing the length element of R_n . Further, $(faU)^i = (f^i a^2 \dots a^\lambda U^{\lambda+1} \dots U^n)$, in which f^i is equal to f^i in $(f' \dots f^\lambda U)$, while the sets of symbols $a^2 \dots a^\lambda$ are equal in any two consecutive brackets $(faU)^{2k-1}$, $(faU)^{2k}$ and otherwise distinct.

The result is then that $K_{2\nu}$, for the space R_λ , is expressible rationally in terms of the coefficients of the first fundamental form of R_n and their derivatives, together with the functions $U^{\lambda+1}, \dots, U^n$ (which define R_λ in R_n) and their derivatives.

§ 3. Expression for K_λ^2 when λ is odd.*

The invariant K_λ^2 (λ odd) can be expressed in a manner similar to the above. Substituting from (57) into (54), one gets

$$(61) \quad G_\lambda^2 = \omega^4 (\omega (fcU)', \omega (faU)^2, \dots, \omega (faU)^\lambda U) \\ \times (\omega (\phi cU)', \omega (\phi bU)^2, \dots, \omega (\phi bU)^\lambda U) (f' \phi' f^3 \dots f^\lambda U) (f^2 \phi^2 \dots \phi^\lambda U).$$

By D. P. (4),

$$\begin{aligned} (\omega (fcU)', \omega (faU)^2, \dots, \omega (faU)^\lambda U) &= \omega^\lambda ((fcU)' (faU)^2 \dots (faU)^\lambda U) \\ &+ \omega^{\lambda-1} (fcU)' (\omega, (faU)^2 \dots (faU)^\lambda U) \\ &+ \omega^{\lambda-1} \sum_{i=2}^{\lambda} (faU)^i ((fcU)' (faU)^2 \dots (faU)^{i-1}, \omega, (faU)^{i+1} \dots (faU)^\lambda U) \\ &\equiv \omega^\lambda \alpha_1 + \omega^{\lambda-1} \alpha_2 + \omega^{\lambda-1} \alpha_3. \\ (\omega (\phi cU)', \omega (\phi bU)^2, \dots, \omega (\phi bU)^\lambda U) &= \omega^\lambda ((\phi cU)' (\phi bU)^2 \dots (\phi bU)^\lambda U) \\ &+ \omega^{\lambda-1} (\phi cU)' (\omega, (\phi bU)^2 \dots (\phi bU)^\lambda U) \\ &+ \omega^{\lambda-1} \sum_{k=2}^{\lambda} (\phi bU)^k ((\phi cU)' (\phi bU)^2 \dots (\phi bU)^{k-1}, \omega, (\phi bU)^{k+1} \dots (\phi bU)^\lambda U) \\ &\equiv \omega^\lambda \beta_1 + \omega^{\lambda-1} \beta_2 + \omega^{\lambda-1} \beta_3. \end{aligned}$$

* See K.-G. C., p. 93.

BIOGRAPHICAL SKETCH

The writer of this dissertation was born at Winchester, Tenn., 1870. His preparation for college was completed at Bellbuckle, Tenn., 1888-90. He entered Vanderbilt University in 1890, and received the A.B. degree in 1894. Three years were then spent as assistant in Battleground Academy, Franklin, Tenn., and the next three years as principal of the Smyrna Fitting School, Smyrna, Tenn. During the next three years, 1900-03, he was a graduate student at the University of Chicago, receiving the A.M. degree in 1902, the thesis being entitled "The determination of all those surfaces for which, when the lines of curvature are taken as parameter lines ($u = \text{const.}$ $v = \text{const.}$) the six fundamental quantities, E , F , G , L , M , N , are functions of one parameter, say u , only." He has been instructor in mathematics at Purdue University since 1903, receiving the title of assistant professor in June, 1910.

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